Embedded Linux Conference
February 21st, 2017
Portland, OR, USA

About the Need to Power Instrument the Linux Kernel

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Today’s Special

- Introduction
- Power Instrumentation:
  - Why?
  - What’s needed?
  - What’s available?
  - What’s missing?
- Conclusion & Next Steps
- Q&A

Introduction

- A major issue the Linux Community faces regarding power management is the lack of power data and instrumentation
  - Dev boards missing probe points
  - Power Measurement equipment expensive / not affordable for many developers,
  - Poor power data publicly available
- This situation is not expected to change in the future
  - Believed that it is only of interest of a handful of developers, where actually everyone is concerned!
- This is forcing ad hoc/custom techniques to be used over and over again.
- Even if not much can be done on the HW side, **power instrumenting** the **Linux Kernel** with standard tooling could definitively help.

Power Instrumentation:

Why?

Power Instrumentation: Purposes (1)

- Holy grail #1: enable dynamic measurement (estimation) of the platform power consumption / battery life, without any power measurement circuitry
  - Any developer could debug power management on any board, with no need of a special (expensive) board

Power Instrumentation: Purposes (2)

- Detect power leaks by dynamically monitoring (tracking) devices power state (Active / Idle / Disabled)
  - Unnecessary running clocks
  - Unnecessary running devices
  - Inadequate CPUFreq/CPUIdle states
    - CPU cores running too fast, low-power C-States not entered
  - Unnecessary powered-on regulators
  - ...

Power Instrumentation: Purposes (3)

- Capture system power trace, and post-process it to
  - Generate use-case power statistics,
  - Generate power charts
- Enable more efficient power debugging
- Enable power consumption regression tracking automation
  - Integrate Continuous Integration (CI) frameworks (KernelCI, PowerCI, fuego, ...)

Power Instrumentation: Purposes (4)

- Model nextgen platform power consumption
  - Applying power data of next SoC revision to an existing power trace

- (... We could even imagine comparing platforms to platforms ... 😉)

Power Instrumentation: Purposes (5)

- Holy Grail #2: closed-loop power management policies
  - Prediction may be improved by measuring the “real” impact of heuristics decisions on platform power consumption
    - E.g. EAS (Energy-Aware Scheduler) platform knowledge could be extended beyond CPU cores
  - Could open the door to self-learning policies / IA / deep learning
    - No more need to fine-tune policies by hand, just let the policies learn the platform!

Power Instrumentation:

What's needed?

What's needed? (1)

1. SW Power Probe points
   - Regulator / Clock / Power Domain / CPU Frequency / CPU Idle / device / GPIO / … power transitions
   - Timestamped

What’s needed? (2)

2. Power consumption data
   - How much power is consumed by a given device in a given power state
     - SoC internal peripherals (CPU, GPU, RAM, UART, I2C, SPI, GPIO, ...)
       - E.g. UART devices consumes 5uW (*) when suspended, 100uW (*) when active
     - Platform peripherals (LCD display, wireless devices, flash devices, sensors, ...)
       - E.g. eMMC device consumes 500uW (*) when suspended, 40mW (*) when active

* Empirical data, for illustrative purpose only

What's needed? (3)

3. Power Analysis Tools
   - Power trace plotting
   - Power trace statistics post-processing
   - Generic / Cross-platform Tools
     - Vendors already have some custom tools of their own, e.g.
       - Qualcomm's Snapdragon Profiler (requires Android)
       - Google's Android Systrace (may require Android too 😉)

Power Instrumentation:

What's available?

FTrace Power Events (1)

- Kernel Probe Points
  - FTrace standard power events
    - RuntimePM events (idle/resume/suspend),
    - Clock Management events (enable/disable/set_rate),
    - CPU power management events (cpuidle/cpufreq/hotplug),
    - Suspend/Resume events,
    - Regulator events (enable/disable/set_voltage),
    - GPIO events (direction/value).
  - FTrace custom events
    - Specific for a given platform

FTrace Power Events (2)

- To trace power events with FTrace
  - Enable CONFIG_FTRACE, CONFIG_DYNAMIC_FTRACE flags in kernel .config file
  - Mount debugfs

    `# mount -t debugfs nodev /sys/kernel/debug`
  - Enable relevant events

    `# echo 1 > /sys/kernel/debug/tracing/events/power/enable`
  - Empty trace buffer

    `# echo > /sys/kernel/debug/tracing/trace`
  - Enable tracing

    `# echo 1 > /sys/kernel/debug/tracing/trace_on`
  - Trace file /sys/kernel/debug/tracing/trace generated with enabled power events

* Note that debugfs interface is used for educational purpose here, but "trace-cmd" binary tool can be used.

FTrace Power Events (3)

- Example of collected power trace

```
# tracer: nop
#
# entries-in-buffer/entries-written: 151941/151941   #P:4
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
[…]
 irq/676-lsm330d-2917  [002] d..2   117.306631: clock_disable: gcc_blsp1_qup6_i2c_apps_clk state=0 cpu_id=2
          <idle>-0     [001] d..2   117.306646: cpu_power_select: idx:1 sleep_time:211893 latency:91 next_event:0
          <idle>-0     [001] d..2   117.306655: cpu_idle: state=1 cpu_id=1
 irq/676-lsm330d-2917  [002] d..3   117.306657: clock_disable: blsp1_qup6_i2c_apps_clk_src state=0 cpu_id=2
          <idle>-0     [001] d..2   117.306662: cpu_idle: state=1 cpu_id=1
          <idle>-0     [001] d..2   117.306677: cpu_idle_enter: idx:1
 irq/676-lsm330d-2917  [002] d..2   117.306686: clock_disable: gcc_blsp1_ahb_clk state=0 cpu_id=2
 irq/676-lsm330d-2917  [002] d..2   117.306712: rpm_suspend: 757a000.i2c flags-d cnt-0  dep-0  auto-1 p-0 irq-0 child-0
 irq/676-lsm330d-2917  [002] d..2   117.306718: rpm_return_int: rpm_suspend+0x36c/0x44c:757a000.i2c ret=0
          <idle>-0     [000] .n.2   117.306808: cpu_idle: state=4294967295 cpu_id=0
          <idle>-0     [001] dn.2   117.307118: cpu_idle_exit: idx:1 success:1
          <idle>-0     [001] dn.2   117.307133: cpu_idle: state=4294967295 cpu_id=1
          <idle>-0     [002] d..2   117.307153: cpu_power_select: idx:1 sleep_time:9972 latency:91 next_event:0
          <idle>-0     [001] .n.2   117.307155: cpu_idle: state=4294967295 cpu_id=1
          <idle>-0     [002] d..2   117.307163: cpu_idle: state=1 cpu_id=2
          <idle>-0     [002] d..2   117.307172: cpu_idle: state=1 cpu_id=2
          <idle>-0     [002] d..3   117.307236: cluster_enter: cluster_name:perf idx:1 sync:0xc child:0xc idle:1
          <idle>-0     [002] d..2   117.307244: cpu_idle_enter: idx:1
 irq/489-d3-i2c--147   [001] d..2   117.307275: clock_disable: gcc_blsp2_qup2_i2c_apps_clk state=0 cpu_id=1
 irq/489-d3-i2c--147   [001] d..3   117.307304: clock_disable: blsp2_qup2_i2c_apps_clk_src state=0 cpu_id=1
 irq/489-d3-i2c--147   [001] d..2   117.307347: rpm_suspend: 75b6000.i2c flags-d cnt-0  dep-0  auto-1 p-0 irq-0 child-0
 irq/489-d3-i2c--147   [001] d..2   117.307355: rpm_return_int: rpm_suspend+0x36c/0x44c:75b6000.i2c ret=0
 irq/489-d3-i2c--147   [001] d..2   117.307385: rpm_resume: 75b6000.i2c flags-4 cnt-1  dep-0  auto-1 p-0 irq-0 child-0
[…]
     ksoftirqd/0-3     [000] d.s3   117.328513: cpufreq_interactive_cpuload: cpu=0 load=27 new_task_pct=0
     ksoftirqd/0-3     [000] d.s3   117.328518: cpufreq_interactive_cpuload: cpu=1 load=16 new_task_pct=0
     ksoftirqd/0-3     [000] d.s2   117.328543: cpufreq_interactive_already: cpu=0 load=27 cur=307200 actual=307200 targ=307200
     ksoftirqd/0-3     [000] d.s3   117.328606: cpufreq_interactive_cpuload: cpu=2 load=4 new_task_pct=0
     ksoftirqd/0-3     [000] d.s3   117.328611: cpufreq_interactive_cpuload: cpu=3 load=0 new_task_pct=0
     ksoftirqd/0-3     [000] d.s2   117.328620: cpufreq_interactive_already: cpu=2 load=4 cur=307200 actual=307200 targ=307200
[…]
   kworker/u8:10-3032  [000] ...1   117.328805: memlat_dev_meas: dev: soc:qcom,memlat-cpu0, id=0, inst=227896, mem=783, freq=36, ratio=291
   kworker/u8:10-3032  [000] ...1   117.328812: memlat_dev_meas: dev: soc:qcom,memlat-cpu0, id=1, inst=17928, mem=50, freq=0, ratio=358
   kworker/u8:10-3032  [000] ...1   117.328887: memlat_dev_meas: dev: soc:qcom,memlat-cpu2, id=2, inst=37313, mem=132, freq=10, ratio=282
   kworker/u8:10-3032  [000] ...1   117.328891: memlat_dev_meas: dev: soc:qcom,memlat-cpu2, id=3, inst=0, mem=0, freq=0, ratio=0
```

FTrace Power Events (4)

- References:
  - https://www.kernel.org/doc/Documentation/trace/ftrace.txt
  - https://www.kernel.org/doc/Documentation/trace/events-power.txt
  - http://elinux.org/Ftrace
  - https://events.linuxfoundation.org/slides/2010/linuxcon_japan/linuxcon_jp2010_rostedt.pdf

Power Instrumentation:
What's missing?

Missing Power "Database" (1)

- Power consumed by all devices of the platform, in any power state
- Not much data published so far, whereas critical
  - Usually only battery lifetime for selected use-cases
- Multi-platform database
  - Mandatory, to enable generic/standard tools
- Example (empirical data, for illustrative purpose only)

```
# cat […]/ftpwrdec/configs/arm64/arm/juno.pdb
# This is a sample power database file, in a human-readable format.
# Device power data format: name (as listed in ftrace), active_pwr (uW) suspended_pwr (uW)
devA, 10000, 10
devB, 1230000, 20
# CPU power data format: cluster id (as listed in ftrace), cpu id  (as listed in ftrace), [frequency (MHz), power (uW)] ...
0, 0, [600, 300000], [900, 800000], [1200, 1200000]
1, 0, [200, 100000], [300, 150000], [500, 200000]
```

- Note Android already manages similar power database
  - power profile, defined in platform/frameworks/base/core/res/res/xml/power_profile.xml

Missing Power “Database” (2)

- Device Tree could also be a candidate
  - Device Tree #1 purpose **IS** to describe the platform to the kernel,
  - Generic / Stable / Multi-platform,
    - Mandatory for new platforms, existing platforms progressively converted
  - « Just a single attribute » to be added to device attributes

```
# cat arch/arm/boot/dts$ cat omap4-panda-common.dtsi
/ {
[…]
&uart2 {
        […]
        active-power = <200>; /* [1] */
        suspended-power = <5>; /* [1] */
};
&hdmi {
        […]
        active-power = <7000>; /* [1] */
        suspended-power = <30>; /* [1] */
};
[…]
```

[1] Empirical data, for illustrative purpose only

Missing Power "Database" (3)

- Power data in Device Tree could be reused by other Kernel components.
  - FTrace
    - E.g. power data added to the trace log
  - Kernel power management policies could reuse it
    - EAS (Energy-Aware Scheduler) / Closed-loop heuristics / deep learning algorithms
- Also accessible from userspace
  - /proc/device-tree/
  - Existing libraries to read DT attributes, e.g. https://github.com/jviki/dtree
- But
  - Could be more difficult to maintain if part of the kernel
    - Longer review process
    - How would device tree maintainers test/validate the data?

FTrace « descrambling » tool (1)

- Static trace analysis
  1. Generate power statistics,
  2. Reformat power trace for standard or dedicated plotting tools
- Multi-platform
  - To handle custom power events and reuse power consumption database
- Could be run directly on the platform or on a host machine
- Very useful for automation / Continuous Integration /power regression tracking
  - Build servers automatically run target use-cases, capture trace, generate the analysis, and generate reports highlighting regressions
  - Power consumption issues could be automatically detected upfront

FTrace « descrambling » tool (2)

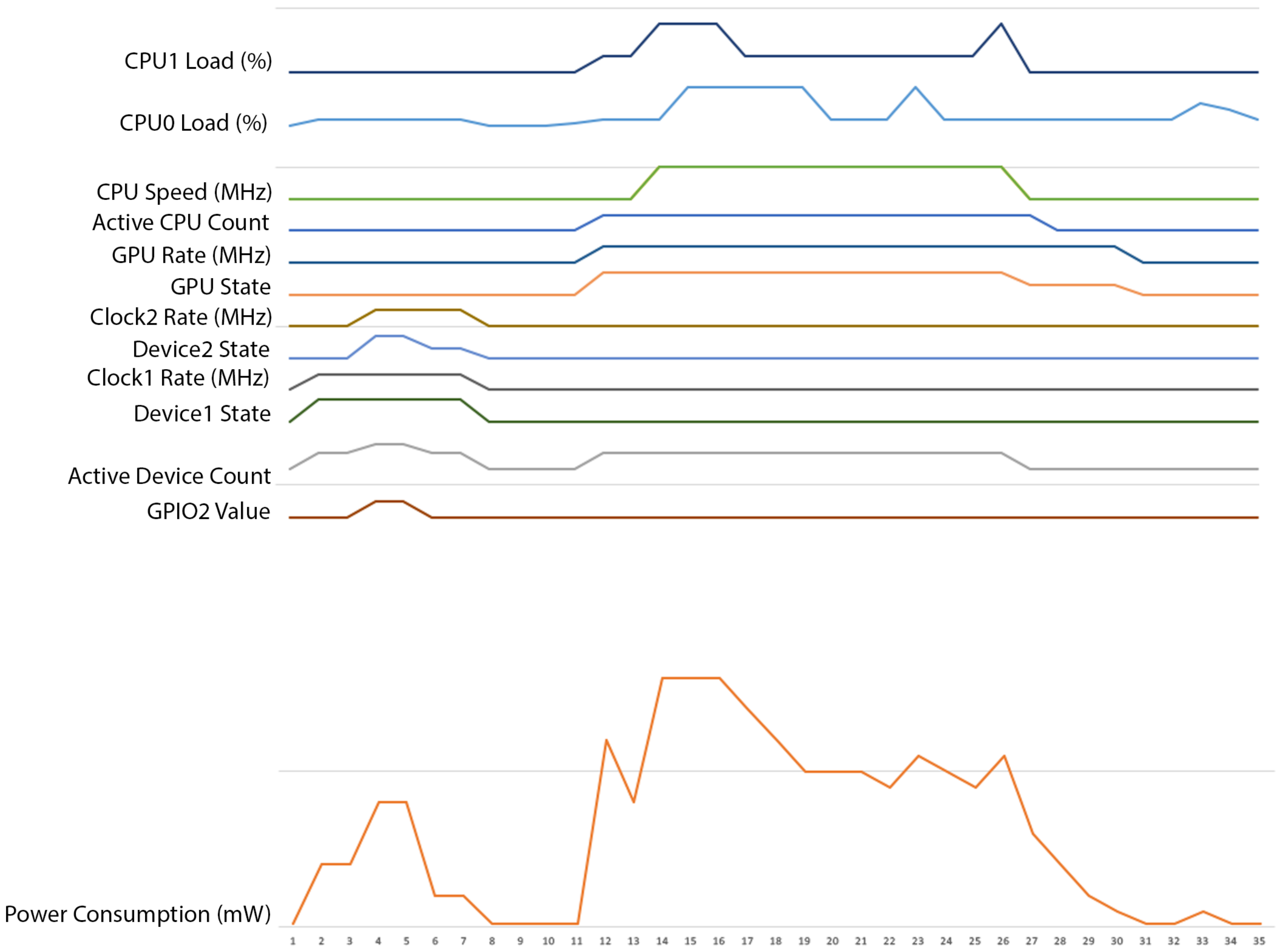
- Example

```
# ./ftpwrdec --plat=arm-juno mypowerftrace
Valid trace file found, descrambling it… done.
|--------------------------------------------------------------|
| Statistics                 | Min    | Max     | Avg    | Count |
| Power Consumption          | 50mW   | 2000mW  | 530mW  |       |
| CPU Loads                  |        |         |        |       |
|  CPU0                      | 12%    | 42%     | 27%    |       |
|  CPU1                      | 05%    | 35%     | 20%    |       |
| CPU Idle Time              |        |         |        |       |
|  CPU0                      | 10ms   | 543ms   | 121ms  |       |
|  CPU1                      | 44ms   | 876ms   | 465ms  |       |
| CPU Frequencies            |        |         |        |       |
|  CPU0                      | 300MHz| 800MHz  |        |       |
|  CPU1                      | 300MHz| 800MHz  |        |       |
| CPU Frequency Changes      |        |         |        | 88    |
| Active Devices             | 05     | 10      |        |       |
| Device Power Transitions   |        |         |        | 69    |
| Active Clocks              | 20     | 30      |        |       |
| Clock Transitions          |        |         |        | 50    |
|[…]                                                            |
|--------------------------------------------------------------|
'Mypowerftrace.xyz' data plotting file generated.
Done.
#
```

FTrace Power Visualization Tool (1)

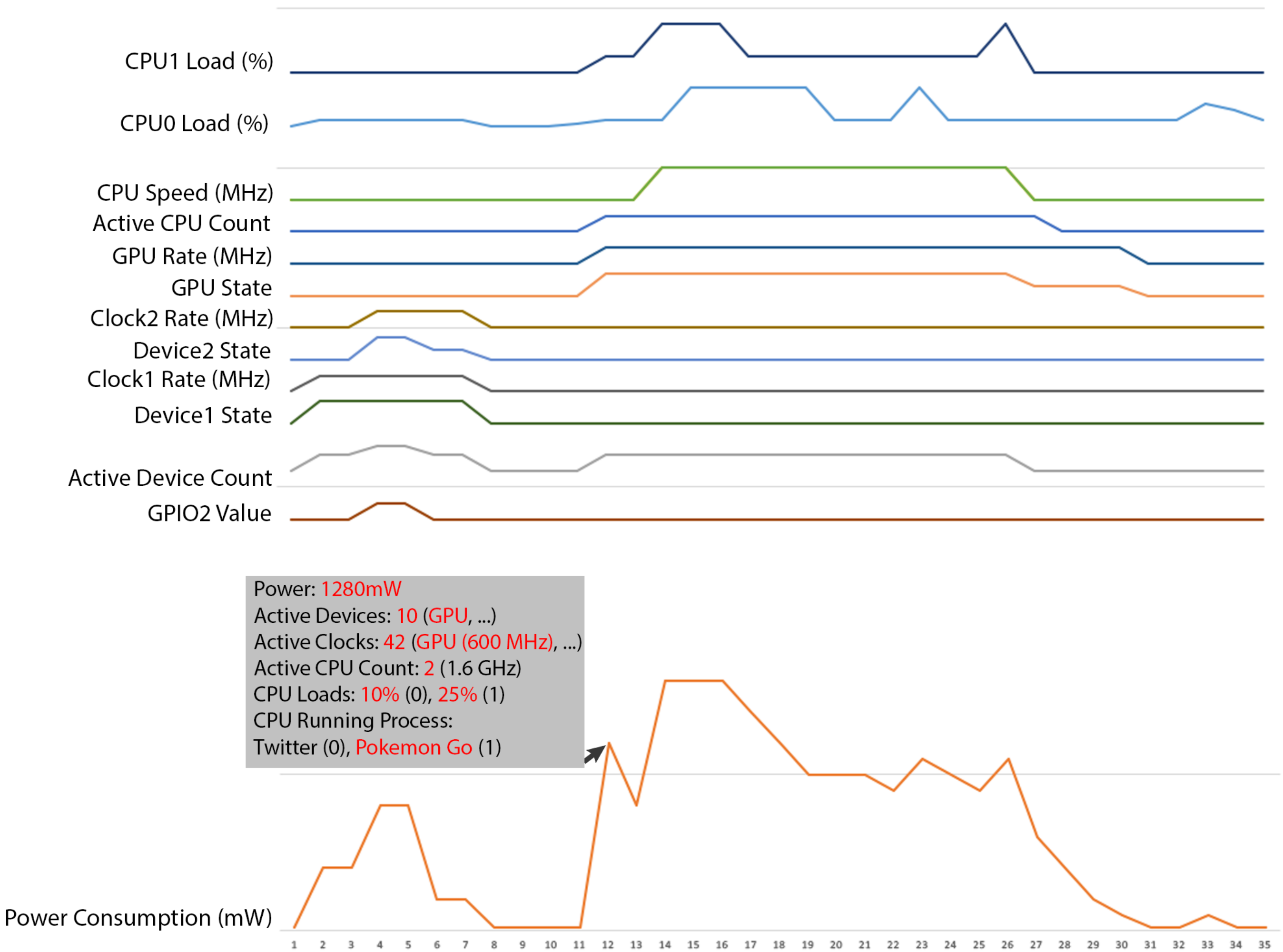
- Static analysis of a trace is not sufficient
- We need a visualization tool that could help us understand the dynamics of the system
  - Like *kernelshark* does for cpu processes
- Plotting in a smart way power events together with the power consumption
  - Pointing a data point on the power consumption curve may highlight
    - Power consumption,
    - Current device power states,
    - Changes compared to previous data point,
    - ...

FTrace Power Visualization Tool (2)



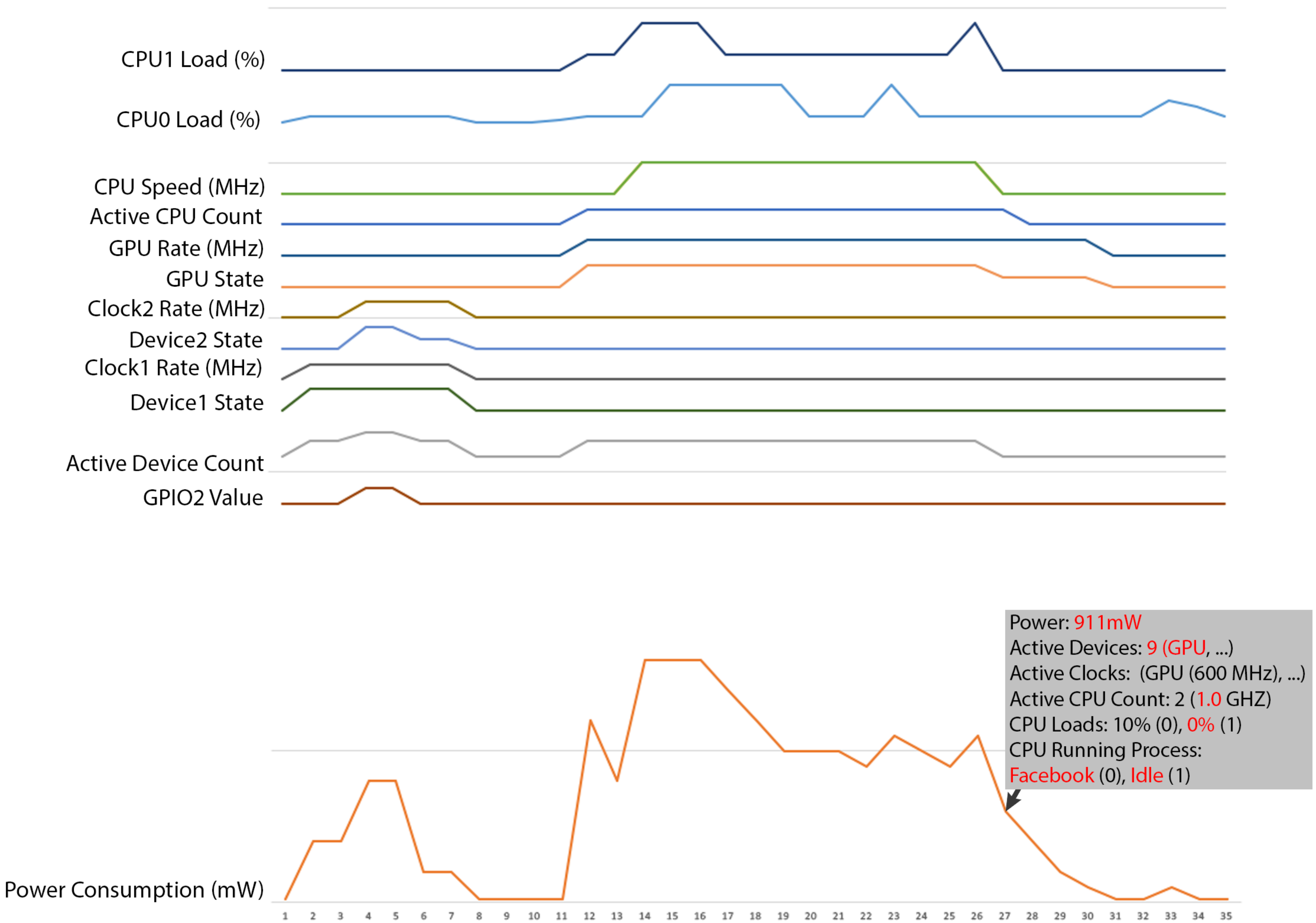
* Empirical data, for illustration purpose only

FTrace Power Visualization Tool (2)



* Empirical data, for illustration purpose only

FTrace Power Visualization Tool (3)



* Empirical data, for illustration purpose only

Power Instrumentation:

Conclusion & What's Next?

Summary

- Bright side:
  - Linux kernel has all infrastructure in place for power instrumentation
    - FTrace power / scheduling / performance / events
    - More relevant events may be relatively easy to be added
    - Tracing performance impact limited to RAM usage
- Dark Side:
  - Missing power consumption data
  - Missing standard analysis/plotting userspace tools

Next Steps

- Next Steps
  1. Collect more feedback and interest from experts during ELC,
  2. Define the power database (incl. device tree vs userspace DB),
     - Probably the most difficult step as it will require a lot of experimentation, and support from vendors
  3. Develop FTrace power events post-processing tool,
  4. Develop power trace visualization tool, and...
     Make it the de-facto standard tool for power debugging 😉

Q & A

Thank you!